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MODELLING OF RAMMED EARTH UNDER SHEAR LOADING

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Abstract. *The intensive use of earth as a building material since ancient times resulted in an important and significant earthen built heritage currently existing worldwide spread. The rammed earth technique has a significant presence in this heritage, where it served to build from simple dwellings to fortresses. However, the high vulnerability of rammed earth constructions to decay agents and to seismic events puts in risk their further existence and the lives of millions of people. With respect to the seismic behaviour of rammed earth walls, the understanding and modelling of their shear behaviour are topics underdeveloped in the bibliography. Nevertheless, these topics are of extreme importance in the preservation and strengthening of rammed earth constructions. Therefore, this paper presents a numerical work aiming at modelling the non-linear behaviour of unstabilised rammed earth under shear loading, resorting to the finite elements method (FEM). The models were used to simulate the behaviour of a set of rammed earth wallets tested under diagonal compression. Both macro- and micro-modelling approaches were considered, where the objective of this last approach was to evaluate the influence of apparent weakness of the interfaces between layers on the shear behaviour. The total strain rotating crack model (TSCRM) was used to simulate the behaviour of the rammed earth material, while the Mohr-Coulomb failure criterion was used to simulate the behaviour of interfaces between layers. Furthermore, uncertainties related to the definition of the input parameters required performing a sensitivity analysis. The numerical models achieved good agreement with the experimental results and the compressive strength, the Poisson's ratio, the tensile strength and the tensile fracture energy revealed to be the most important parameters in the analyses.*

1 INTRODUCTION

The concept of earth construction is tightly related with the concept of vernacular architecture, since these constructions are typically built using local soils and other resources. This type of construction is used since ancient times, as is shown by archaeological evidences from millenarian cities built entirely with earth, such as Jericho (Israel), Çatal Huyuk (Turkey), Harappa (Pakistan), Akhlet-Aton (Egypt), Chan-Chan (Peru), Babylonia (Iraq) and Duheros (Spain) [1].

In 1982, the World's population living in a house built with raw earth was estimated to be of about one third [2], whereas nowadays is estimated to be of about one fourth, as argued by Jaquin [3]. These numbers emphasise the importance of earth constructions around the world with respect to the sheltering problem. Furthermore, the intensive use of earth as a building material also resulted in several examples of sites with relevant cultural and architectural values, which are important to be preserved.

The preservation of the earthen built heritage demands frequent conservation interventions, since earth constructions are very sensitive against external agents, such as rainfall, wind, rising damp, soil settlements and earthquakes. The absence of these interventions leads to the fast decay of these constructions [4] in the form of cracking, reduction of the bearing cross sections and reduction of the mechanical properties of the earthen materials. These types of damage have obvious negative impact on the structural performance of these constructions. Furthermore, earth constructions are acknowledged by an intrinsic poor seismic behaviour [5], meaning that these issues are particularly sensitive in regions with non-negligible seismic hazard.

Rammed earth, also known as "*taipa*", "*taipa de pilão*", "*tapial*", "*pise de terre*", "*pisé*" or "*stampflehm*", is one of the most popular earth construction techniques and consists in compacting moist earth by layers inside a formwork to build monolithic walls. In general, the earth used is characterized by a broad particle size distribution, ranging from clay to gravel size, which promotes a material with high density upon compaction. The addition of lime is a practice every so often observed in existing rammed earth constructions, especially in the case of the military fortresses of the Iberian Peninsula [6, 7]. The compaction of traditional rammed earth is carried out resorting to manual rammers made from timber, which results in a characteristic horizontal layering. In fact, the use of the formwork constitutes a key feature and differentiates this technique from other earth construction techniques [2, 8]. A traditional formwork is, in general, supported directly on the wall by means of putlogs crossing the entire thickness of the wall, and is dislocated horizontally as the rammed earth blocks are built. Therefore, the construction of a wall is carried out by courses (like masonry), where the formwork runs horizontally along the perimeter of the construction and then is lifted to build the next course [9]. The presence of putlog holes between courses is also common and results from the removal or deterioration of the putlogs. The dimensions of the rammed earth blocks are very variable from country to country, from region to region or even within the region; for example in Alentejo (Portugal) the length of rammed earth blocks from typical dwellings may vary from 1.40 to 2.50 m, the height from 0.40 to 0.55 m and the thickness from 0.40 to 0.57 m [10].

Comprehending the structural behaviour of rammed earth constructions is of extreme importance for their conservation. This requires deep knowledge on the material properties and failure mechanisms [11]. However, this information is still very limited and scattered in bibliography [12]. The numerical modelling of rammed earth is also an important tool for decision making in the conservation of rammed earth constructions. However, references on the modelling of rammed earth constructions by the finite element method (FEM) are hardly found in literature. In fact, the few known studies [13-15] adopted very simple models, which included very simple constitutive laws for the materials (such as linear elastic isotropic and elastic-perfectly plastic behaviour). In general, these models were used to predict stress levels and to simulate possible collapse mechanisms. The simulation of the deformability and shear behaviour of rammed earth constructions are topics usually not addressed. However, these are fundamental for understanding and predicting the behaviour of rammed earth construction in the case of a seismic event, where their structural behaviour is expected to be governed by the non-linear behaviour of the material.

On the other hand, complex constitutive laws requires detailed information on the properties of rammed earth materials, which is not always available or is available from a limited quantity of experimental tests. Moreover, the variability found in raw earthen materials brings up even more uncertainties regarding the characterization of the materials and to the modelling. A compromise should be found between representativeness, reliability, accuracy and complexity of the constitutive model with respect to the material behaviour, namely regarding the computational demand of the analysis.

This paper presents a numerical work aiming at modelling the non-linear behaviour of unstabilised rammed earth under shear loading. The models were calibrated by taking into account a set of compression and diagonal compression tests carried out at BAM laboratories (Federal Institute for Materials Research and Testing, Berlin) [16]. The non-linear constitutive law adopted is based on the total strain rotating crack model implemented in DIANA software [17]. This type of models was chosen because they have been used successfully for capturing the global seismic behaviour of historical masonry [18], and are relatively common in software for FEM analysis. Both macro- and micro-modelling approaches were considered for the simulation of the diagonal compression tests, and the respective FEM models were calibrated according to the experimental results. The micro-modelling approach was intended to evaluate the influence of apparent weakness of the interfaces between layers on the shear behaviour of rammed earth [19]. Finally, a sensitivity analysis of the parameters involved was carried out to investigate the influence of the variability and uncertainties of the properties of rammed earth on the FEM models.

2 EXPERIMENTAL DATA

The experimental program carried out at BAM laboratories included the testing of five unstabilised rammed earth wallets under axial compression and another five under diagonal compression. The wallets were compacted with 6 layers with an average thickness of about 84 mm (Figure 1). The resulting average dimensions of the wallets were of about 499 x 505 x 117 mm^3 (width x height x thickness). The average bulk density was of about 2190 kg/m^3.The soil used for manufacturing the specimens presented percentages of clay, silt and sand plus gravel of about 11%, 25% and 64%, respectively.

(a) (b) (c) (d)

Figure 1: Manufacturing of the rammed earth wallets [16]: (a) earth mixture; (b) filling of the formwork with one layer; (c) compaction of the layer; (d) demoulding after compacting.

The wallets were tested after drying the specimens in a climate room at 23ºC of temperature and 50% of relative humidity.

2.1 Axial compression tests

The compression tests were carried out under displacement control, where the testing speed was defined such that the failure occurred within 20-30 min (see [16] for further details). Linear variable differential transformers (LVDTs) were used for measuring the deformation of the specimens, as depicted in Figure 2a. The axial stress-strain curves obtained from the compression tests of the specimens are presented in Figure 2b, as well as the respective envelope. These curves thoroughly highlight the non-linear behaviour of rammed under compression, which starts from low stress levels. Furthermore, it was obtained average values for compressive strength (f_c), Young modulus (E_0), and Poisson ratio (v) of about 3.7 N/mm^2, 4207 N/mm^2 and 0.27, respectively.

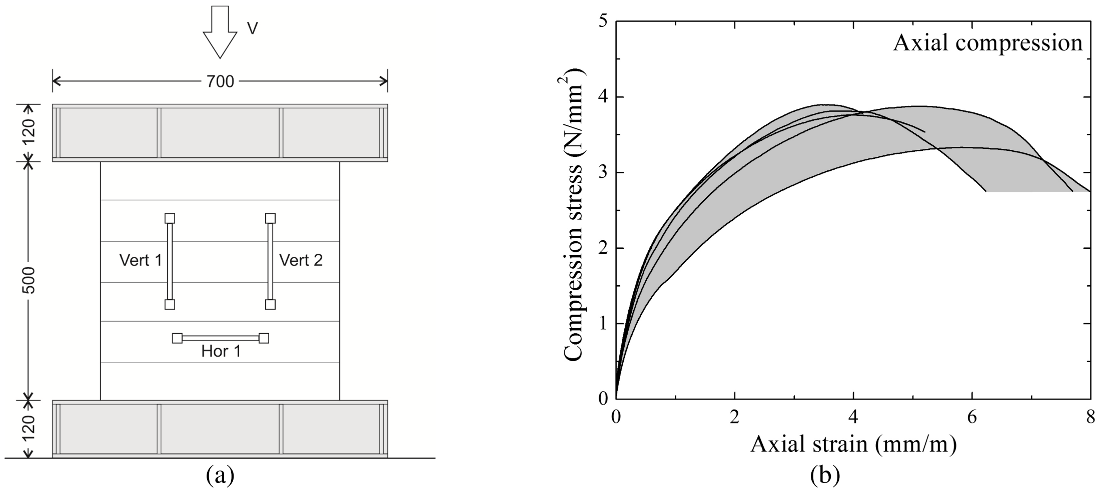

Figure 2: Axial compression tests: (a) test setup (dimensions in mm); (b) compression stress – axial strain curves.

2.2 Diagonal compression tests

The diagonal compression tests were performed following the procedure given in ASTM E 519-10 [20]. The test setup is presented in Figure 3a, from which is highlighted the geometry of the supports and disposition of the LVDTs placed at both faces of the specimens. The contact between the specimens and the supports was regularized by means of a low strength cement mortar (see [16] for further details). Figure 3b presents the shear stress – shear strain curves of the specimens, as well as the respective envelope. In general, the wallets exhibited an early peak shear stress, which was followed by shear hardening. It should be noted that the shear hardening phase imparts most of the shear deformations of the curves. Furthermore, the average values obtained for the shear strength (f_s) and shear modulus (G_0) were 0.70 N/mm^2 and 1582 N/mm^2, respectively.

In general, the failure of the wallets was preceded by the appearance of a crack close to the early peak shear stress. Then, further cracks developed forming a system of cracks crossing diagonally the specimen from the top to the bottom support (Figure 4). Cracking at the interfaces between layers was also observed, where the diagonal systems of cracks tended to follow partially this interface. Cracks also appeared at the borders of the wallets in the interfaces between layers, developing towards the middle. This observation shows that these interfaces can behave as weakness surfaces, where delamination failure might occur when the material is sheared or tensioned due to a seismic event, for instance.

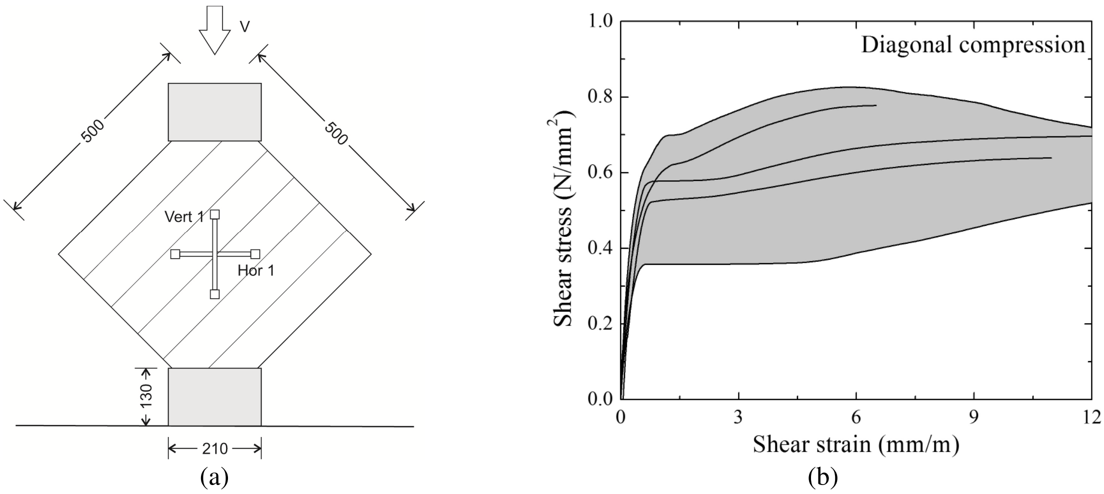

Figure 3: Diagonal compression tests: (a) test setup (dimensions in mm); (b) shear stress – shear strain curves.

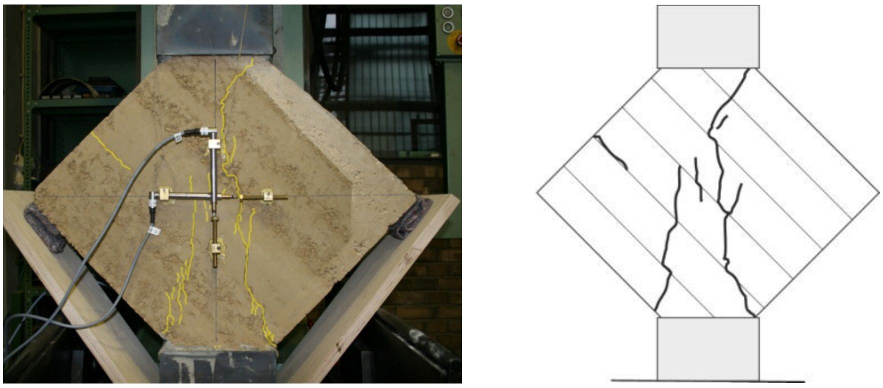

Figure 4: Crack pattern of a wallet tested under diagonal compression [16].

3 FEM MODELLING

The numerical modelling of the diagonal compression tests was carried out resorting to the finite element method (FEM), where both the macro- and micro-modelling approaches were considered. In the first approach, the rammed earth material was treated as a homogeneous continuum medium, which allows obtaining models with lower complexity than those obtained from a micro-modelling approach. In this last case, the rammed earth material was treated as a set of stacked layers of finite elements to simulate the interfaces between compaction layers. This approach was previously used by Jaquin et al. [14] to simulate the delamination failure mechanism of rammed earth walls experiencing concentrated loads. The models were prepared and computed using the FEM software DIANA 9.4 [17].

3.1 Geometry, boundary conditions and loading

The average dimensions of the specimens tested were taken as the dimensions of the numerical models (see Section 2) and a plane stress state was assumed. Eight-noded quadrilateral elements (CQ16M) were used to simulate the rammed earth material in both macro- and micro-modelling approaches. In the micro-modelling approach, interfaces between layers were simulated resorting to six-noded zero thickness interface elements (CL12I). The boundary conditions were defined by considering a width of the supports of about 125 mm. The supports were considered as providing full confinement and the load was applied by imposing vertical displacements on the constrained nodes at the top of the model. The self-weight of the material was not considered in the analyses, since its contribution for the stress state was expected to be marginal.

3.2 Constitutive laws

The total strain rotating crack model (TSRCM) was selected to simulate the behaviour of the rammed earth material [17]. The TSRCM corresponds to a model of distributed and rotating cracks based on total strains, where the crack direction rotates with the principal strain axes [21-23]. The TSRCM implemented in DIANA software [17] integrates several possible non-linear stress-strain relationships according to the type of stress involved, namely compression and tension. The relationship in compression was initially assumed to be parabolic, but this assumption was unable to simulate the non-linear behaviour observed in the experimental tests (see [24] for further details). This situation lead to adopt a multi-linear relationship based on the average curve of the compression tests (see Figure 5a), which allows a more adaptable simulation of the compressive behaviour. The second point of the multi-linear relationship was defined for $0.3f_c$ by taking into account the experimental Young's modulus. The relationship in tension was assumed to be exponential, as depicted in Figure 5b.

The crack bandwidth (h) of the elements was assumed to be dependent of the area of the element (A), according to Equation (1). This assumption allows making the results of the numerical analysis independent from the size of the finite element mesh.

$$h = \sqrt{A} \tag{1}$$

Table 1 presents the initial values assumed for the parameters required by the TSRCM. The average results obtained from the axial compression tests were used to define the initial values of the Young's modulus (E_0) and Poisson's ratio (υ). The initial values of the remaining parameters were assumed with basis on recommended values for masonry. The tensile strength (f_t) was estimated as $0.1f_c$ and the mode-I tensile fracture energy (G^I_f) as $0.029f_t$.

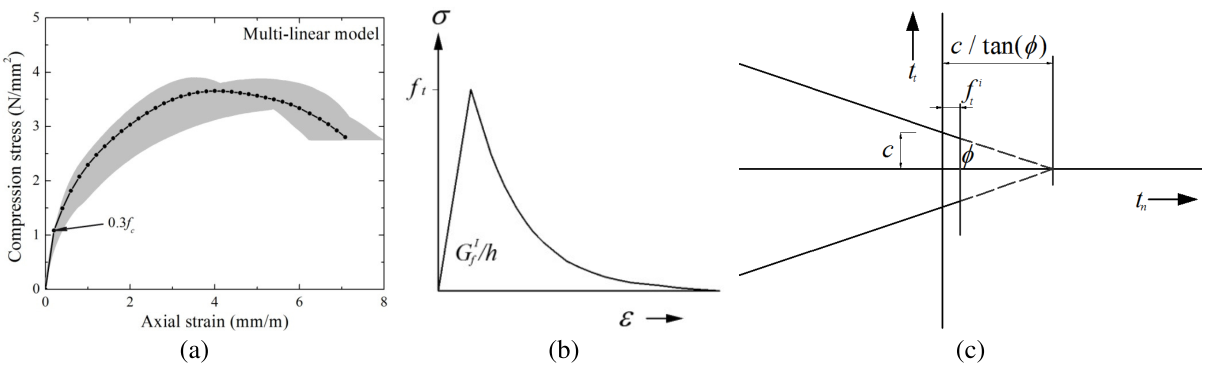

Figure 5: Material models adopted in the numerical modelling: (a) stress-strain relationship in compression; (b) stress-strain relationship in tension; (c) Coulomb friction model used in the interfaces.

Table 1: Initial values of the parameters assumed for the TSRCM of the rammed earth layers.

Material	E_0 (N/mm^2)	υ (-)	f_t (N/mm^2)	G^I_f (N/mm)
Rammed earth	4207	0.27	0.37	0.0109

The interface elements of the micro-model were modelled using the non-linear Coulomb friction model (Figure 5c) implemented in DIANA software [17]. The parameters required by this model were neither determined experimentally nor available in the literature for the case of rammed earth. This means that these parameters had to be carefully estimated and the initial values are presented in Table 2. The initial values of the interface normal stiffness (k_n) and of the shear stiffness (k_t) were assumed to be very high, to avoid concentrating the elastic deformations in the interface elements. Therefore, k_n was assumed as $100E_0$ and k_s was estimated resorting to Equation (2). These values were shown to be adequate in numerical models simulating the compression tests [24]. The cohesion (c) was estimated as a function of the tensile strength estimated for the rammed earth, namely as $1.5f_t$. The friction angle (ϕ) was assumed to be 37º and the dilatancy angle (ψ) as zero. The tensile strength of the interfaces (f_t^i) was defined as $2/3f_t$, while taking into account that the maximum value mathematically allowed by the model is $c/\tan(\phi)$. It should be noted that the displacements after failure are determined following the flow theory of plasticity, as described by TNO [17]. Finally, the tensile behaviour of the interfaces was assumed as brittle.

$$k_s = \frac{k_n}{2(1+\nu)} \tag{2}$$

Table 2: Initial values of the parameters assumed for the Coulomb friction model of the interfaces between layers.

Material	k_n (N/mm^3)	k_t (N/mm^3)	c (N/mm^2)	$\tan(\phi)$ (-)	$\tan(\psi)$ (-)	f_t^i (N/mm^2)
Interfaces	$4.21\text{x}10^5$	$1.66\text{x}10^5$	0.56	0.75	0	0.25

3.3 Calibration of the models and results

Figure 6a presents the shear stress – shear strain curves of the macro- and micro-model of the diagonal compression tests using the reference values. Both models present similar curves and a behaviour much more brittle than that of the experimental curves. This means that the calibration of the models requires adjusting G^I_f, which is the parameter controlling the brittleness. Figure 6b depicts the curves of the calibrated models, which resulted from an increase of the initial value of this parameter in about 10 times. This important increase is justified by the fact that rammed earth behaves more as a monolithic material than masonry does. Furthermore, the rammed earth features a broad PSD, which is thought to have great contribution for the interlocking at the crack surface, by promoting its roughness. This enhances the fracture energy of rammed earth relative to historical masonry, where cracking occurs mostly at less rough surfaces, namely the interfaces between mortar and masonry units.

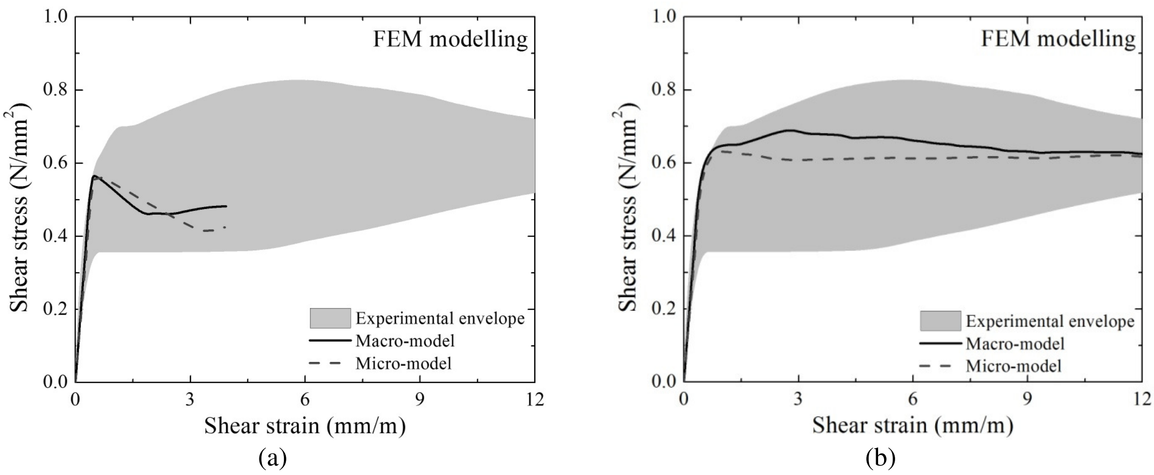

Figure 6: Behaviour of the macro- and micro-model of the diagonal compression tests: (a) using the initial parameters; (b) after calibration.

The curve of the macro-model is characterized by an early peak shear stress, followed by a small shear hardening until the maximum shear stress is achieved. On the other hand, the curve of the micro-model does not exhibit this early peak shear stress. Instead, the model achieves first the maximum shear stress, followed by a drop in stress with a subtle shear softening. Possibly, this drop in stress is related to the failure of interface elements, which is then compensated with stress redistribution. However, the development of the macro-model curve is closer to those obtained from experimental tests. The macro-model presents higher maximum shear stress than the micro-model, whose values are, respectively, 0.69 N/mm^2 and 0.63 N/mm^2. Both values correspond to a minor underestimation of the average shear strength obtained from the experimental tests (0.70 N/mm^2). In general, it is shown that both curves fit within the experimental envelope, meaning that the use of the TSRCM might provide good results when modelling full rammed earth structures.

The failure modes of both models were also analysed. Figure 7 presents the tensile principal strains obtained for an imposed vertical displacement of 1.00 mm. The damage of both models is shown to concentrate at the middle, due to the development of tensile stresses, and at the supports, due to stress concentration. This corresponds to the evolution of the system of cracks observed in the experiments.

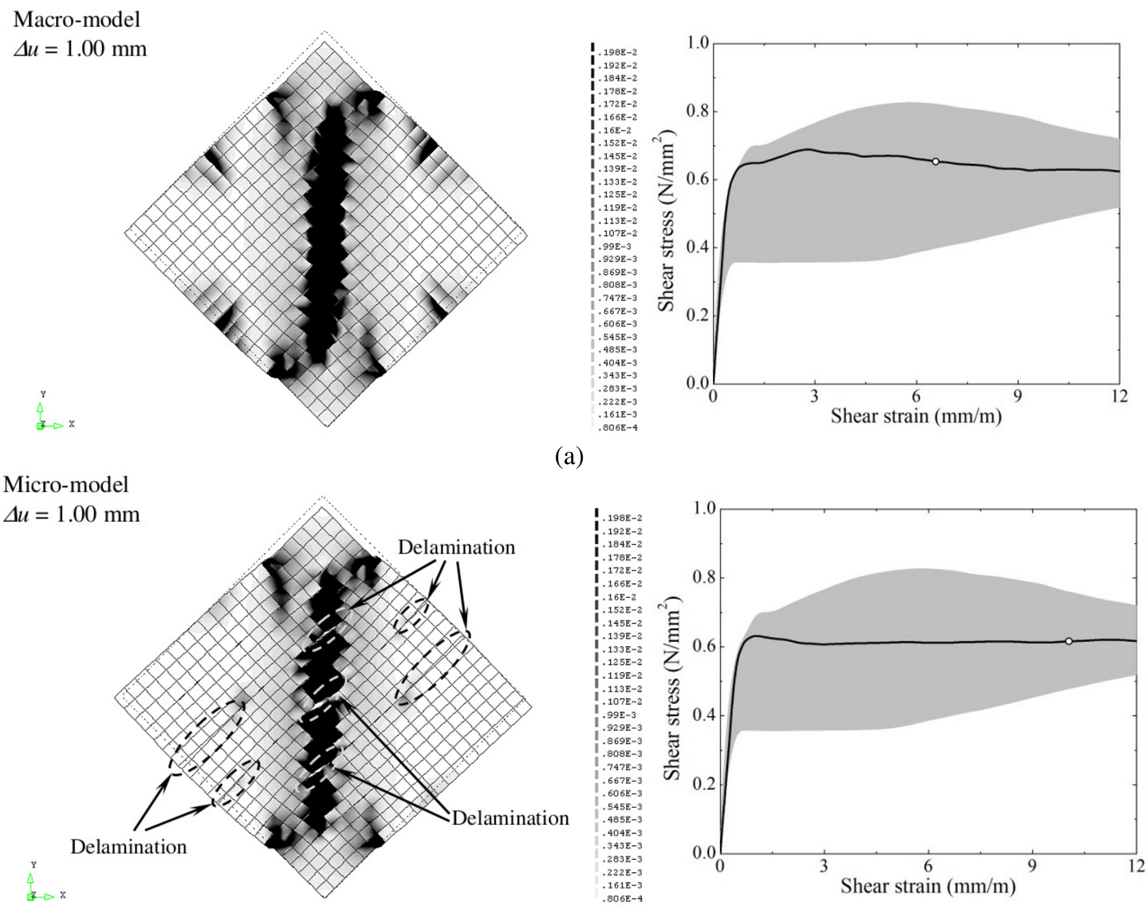

Figure 7: Tensile principal strains for an imposed vertical displacement of 1 mm: (a) macro-model; (b) micro-model.

In the macro-model, damage is also observed to occur at the four borders of the model, which indicates that these regions are vulnerable to the occurrence of delamination failure.

The micro-model confirms the occurrence of this failure mode, since it is possible to observe failure of interface elements at two of the borders, as also observed in the experimental tests. Furthermore, this model also shows that delamination can also occur in the middle region, where the diagonal system of cracks is developed. In general, both models are capable of detecting potential zones of failure by delamination. However, the macro-model does not allow controlling this failure mode, neither allows differentiating it from failure in the rammed earth material.

4 SENSIVITY ANALYSIS

A sensitivity analysis was performed to assess the influence of the mechanical properties variability on the rammed earth shear behaviour. The definition of some of these properties in the macro- and micro-model lacked on reliable sources for their definition, especially with respect to the properties of the interface elements. Thus, the main objective of this sensitivity analysis was to assess how the variability of these parameters can affect the response of the calibrated macro- and micro-models. The sensitivity analysis was performed by changing parameters accounting for compression, tension, interface and geometrical properties, as summarised in Table 3.

Table 3: Parameters considered in the sensitivity analysis.

Parameter	Reference value	Lower value	Upper value
Young's modulus (N/mm^2)*	$E_{0,ref}$ = 4207	$0.5E_{0,ref}$ = 2104	$2E_{0,ref}$ = 8414
Poisson's ratio (-)	υ_{ref} = 0.27	υ_{low} = 0.1	υ_{upp} = 0.4
Compressive strength**	$f_{c,ref}$	$0.8f_{c,ref}$	$1.2f_{c,ref}$
Tensile strength (N/mm^2)	$f_{t,ref}$ = 0.37	$0.5f_{t,ref}$ = 0.19	$2f_{t,ref}$ = 0.74
Tensile fracture energy (N/mm)	$G^I_{f,ref}$ = 0.109	$0.2\,G^I_{f,ref}$ = 0.022	$5\,G^I_{f,ref}$ = 0.545
Cohesion (N/mm^2)	c_{ref} = 0.561	$0.5c_{ref}$ = 0.281	$2c_{ref}$ = 1.122
Friction angle	$\tan(\phi_{ref}) = \tan(37°)$	$\tan(\phi_{low}) = \tan(20°)$	$\tan(\phi_{upp}) = \tan(50°)$
Interface tensile strength (N/mm^2)	$f^i_{t,ref}$ = 249	$0.5f^i_{t,ref}$ = 125	$2f^i_{t,ref}$ =498
Layer thickness (mm)	$t_{lay,ref}$ = 84	$0.5t_{lay,ref}$ = 4.2	$1.5t_{lay,ref}$ = 12.6

* the value of the Young's modulus was changed in the multilinear relationship by considering only the first point ($0.3f_c$), being the rest of the curve translated.
** the value of the compressive strength value was changed by applying a scale factor to the multilinear relationship, while keeping the reference value of the Young's modulus.

The compressive strength, the Poisson's ratio, tensile strength and tensile fracture energy are the parameters with the highest influence on the maximum shear stress of both models. In the case of the macro-model, this statement can be easily visualized in Figure 8, where the non-dimensional maximum shear stress (normalised by the maximum shear stress of the calibrated model – $f_s/f_{s,ref}$) is compared with the non-dimensional parameters tested in the sensitivity analysis (normalised by the respective parameter of the calibrated model – x/x_{ref}). Figure 9 makes the same comparison for the case of the micro-model, but includes also the interface parameters. The interface parameter with the greatest influence is the cohesion, especially when it is decreased. On the other hand, the other parameters seem to have little influence.

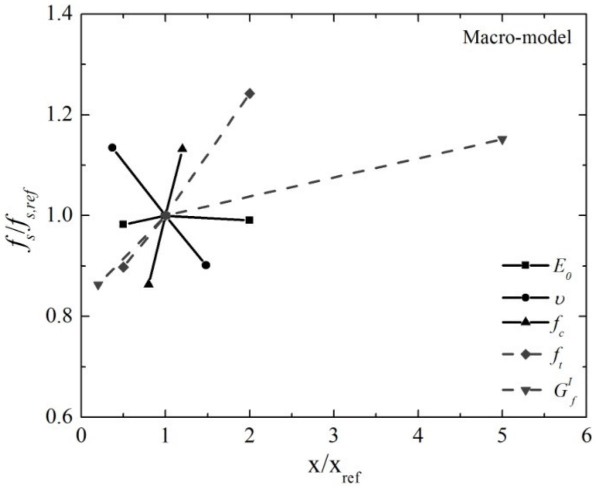

Figure 8: Non-dimensional relationship between the maximum shear stress and the parameters varied (macro-model).

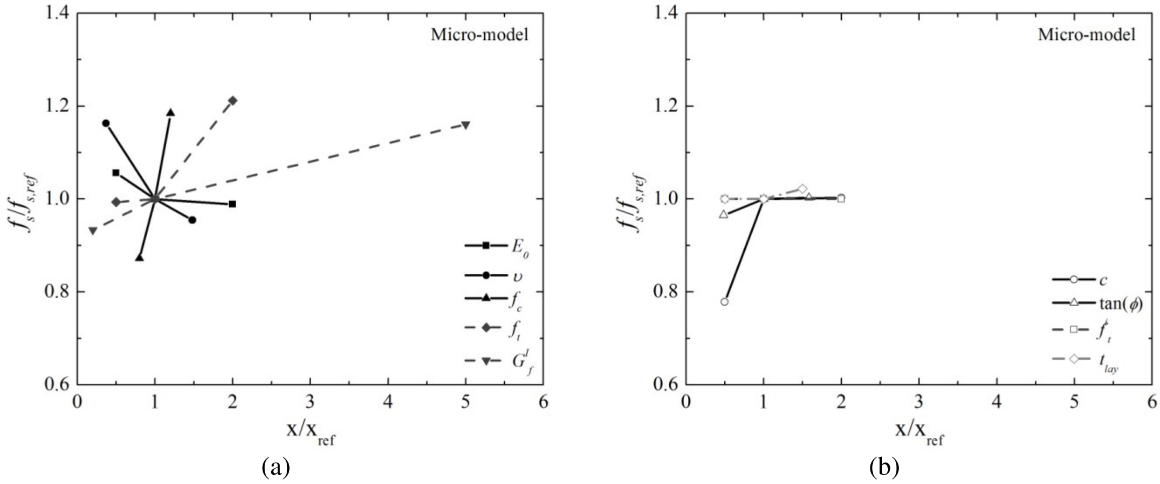

Figure 9: Non-dimensional relationship between the maximum shear stress and the parameters varied (micro-model): (a) layer parameters; (b) interface parameters.

5 CONCLUSIONS

This paper deals with the numerical simulation of rammed earth wallets under shear loading. The numerical models were calibrated with the experimental results of an experimental program, which consisted in the testing of several rammed earth wallets under diagonal compression. Numerical models of the diagonal compression tests were prepared according to the macro- and micro-modelling approaches. The TSRCM was used to simulate the behaviour of the rammed earth material, while the Mohr-Coulomb failure criterion was used to model the interfaces between layers. After calibration, a sensitivity analysis was carried out to assess the influence of the uncertainties of the input parameters on the shear behaviour of the models.

In general, the calibrated macro- and micro-models demonstrated behaviour in good agreement with the experimental envelope of the shear stress – shear strain curves and with the experimental damage pattern. The micro-model allowed capturing the failure by delamination of the interfaces between layers, like observed in the experimental tests. This feature revealed to be the main advantage of this approach, yet the macro-model seemed to provide an equivalent numerical simulation of the shear behaviour.

The sensitivity analysis performed for both models showed that the compressive strength, the Poisson’s ratio, the tensile strength and the tensile fracture energy are the parameters with the greatest influence on the maximum shear stress. Thus, experimental investigations on the mechanical behaviour of rammed earth should address carefully the determination of these parameters. Regarding the parameters of the interface elements, the cohesion is that with the greatest influence.

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